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THE FLUIDIZED BED COMBUSTION OF A MEDIUM VOLATILE BITUMINOUS COAL FROM BRITISH COLUMBIA

BY

E.J. Anthony*, D.L. Desai** and F.D. Friedrich*

ABSTRACT

Byron Creek, a bituminous coal from British Columbia, was burnt in a pilot scale atmospheric fluid bed combustor (with a cross section of 0.155 m^2). Some of the surface seams of this coal are partially oxidized and coal from an oxidized portion of such a seam was used in this study.

A test matrix requiring three bed temperatures (800°, 900°, and 1000°C); three fluidizing velocities (1.8, 2.4 and 3 m/s) and one excess oxygen level of 4% was employed. Ten of the tests were carried out with fly ash recycle and the remaining nine tests were carried out without recycle.

Without recycle the combustion efficiencies varied from 70 to 90%. With recycle they rose to 93 to 98%. Attempts to correlate carbon carryover, fcc, with fluidizing velocity (expressed as a dimensionless fluidizing velocity $p = gL/u^2$ where g is the acceleration due to gravity; L, a characteristic length, in this case 406 mm, the length of one side of the bed and U is the fluidizing velocity) and bed temperature gave the following result:

$$fcc = 0.139\ p^{-0.348} \exp\left(\frac{5740}{T}\right)$$

Varying the number of cooling tubes in the bed from 2 to 20 for these tests did not affect the correlation. No such correlation could be developed for tests with recycle.

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Trials with recycle had higher combustion efficiencies when the bed temperatures were high and the fluidizing velocities were low. However, attempts to determine the dependence of the combustion efficiency on the recycle rate, either expressed directly or as a ratio of the feed rate were unsuccessful.

The bedside heat transfer coefficients H_w for the inbed cooling tubes were determined. The majority of these ranged from 300 to 400 W/m^2 K.

The emissions from the bed were within acceptable limits. NO_x levels varied from 20 to 350 ppm; SO_2 from 200 to 370 ppm and CO concentrations from 100 to 1500 ppm.

LA COMBUSTION EN LIT FLUIDISÉ DU CHARBON SUBBITUMINEUX MOYENNEMENT VOLATIL DE LA COLOMBIE-BRITANNIQUE

par

E.J. Anthony*, D.L. Desai**, F.D. Friedrich*

RÉSUMÉ

Le charbon subbitumineux de Byron Creek en Colombie-Britannique a été brûlé dans un four pilote à combustion en lit fluidisé à la pression atmosphérique (la section droite du four mesure 0,155 m^2). Quelques couches de surface de ce charbon ont été oxydées. On a effectué la présente étude à partir d'une de ces couches.

On a utilisé une matrice à trois températures de lit (800, 900 et 1000°C), à trois vitesse de fluidisation (1,8, 2,4 et 3 m/s) et à un niveau d'excès d'oxygène de 4%. On a fait recirculer les cendres volantes pour seulement dix des dix-neuf essais.

Sans la recirculation des cendres volantes, le rendement de la combustion varie de 70 à 90%. Avec la recirculation, le rendement se situe entre 93 et 98%. La mise en corrélation de l'entraînement du carbone (fcc) avec la vitesse de fluidisation (exprimée par une vitesse de fluidisation sans dimension selon la formule $p = gL/u^2$ où g est l'accélération due à la gravité, L la longueur caractéristique, 406 mm dans le cas présent, c'est-à-dire la longueur d'un côté du lit, et u la vitesse de fluidisation) et la température de lit a donné le résultat suivant:

$$fcc = 0{,}139\ p^{-0.348}\ \exp\left(\frac{5740}{T}\right)$$

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Lors de ces essais, on a fait varié de 2 à 20 le nombre de tubes de refroidissemnet, sans que la mise en corrélation en soit toutefois changée. Il a été impossible d'établir une mise en corrélation de ce genre pour les essais effectués sans recirculation.

On a obtenu un rendement de combustion plus élevé avec la recirculation lorsque la température du lit était élevée et la vitesse de fluidisation faible. Cependant, les essais effectués dans le but de déterminer la relation entre le rendement de combustion et la vitesse d'alimentation, ont été infructueux.

On a déterminé les coefficients de transmission de chaleur (H_w) pour les tubes de refroidissement dans le lit. La plupart des coefficients varient de 300 à 400 W/m^2 K.

Les émissions du lit se situent à l'intérieur des limites acceptables. Le taux de NO_x varie de 20 à 350 ppm et celui de SO_2 de 200 à 370 ppm. La concentration en CO se situe entre 100 et 1500 ppm.

INTRODUCTION

Energy, Mines and Resources is encouraging the development of fluidized bed combustion (FBC) technology. In-house pilot-scale research at the Combustion and Carbonization Research Laboratories (CCRL) is directed towards the study of the performance of various low grade or high sulphur Canadian fuels in fluidized bed combustors.

As part of that effort Byron Creek, a western bituminous coal from British Columbia, taken from an oxidized portion of a seam, was burnt in CCRL's pilot-scale atmospheric fluidized bed combustor (AFBC). The bed has internal dimensions of 380 x 410 mm and was operated with a mean bed depth of 630 mm employing in-bed fuel feed.

A test matrix was used for this work: employing three bed temperatures (800°, 900° and 1000°C), three fluidizing velocities (1.8, 2.4 and 3 m/s) and one excess oxygen level (4%). Tests were carried out under identical conditions both using recycle (ten tests) and without fly ash recycle (nine tests) to determine the effect on combustion efficiency.

Bed temperatures were controlled via in-bed stainless steel cooling tubes. From 2 to 20 tubes, connected together in series to form a number of cooling circuits, were used in these tests. The individual circuits were monitored by thermocouples and controlled by manually adjusted valves. The in-bed cooling tubes had a O.D. of 21.3 mm and an I.D. of 15.8 mm.

RESEARCH OBJECTIVES

The objectives of the AFBC trials with Byron Creek coal were to determine combustion efficiency with and without recycle, as a function of bed conditions when firing 50 mm x 0 size coal. A secondary objective was to measure emission levels, specifically of NO_x, SO_2 and CO. In addition information concerning the value of the heat transfer coefficient for the inbed tubes was sought. These aims may be stated more specifically as follows:

a) To determine the combustion efficiency as a function of bed temperature and fluidizing velocity.

b) To determine the effects of fly ash recycle and recycle rate on combustion efficiency.

c) To determine the effect of bed conditions on the emissions of NO_x, SO_2 and CO.

d) To determine the heat transfer coefficients and heat transfer rates to the inbed cooling tubes.

COAL CHARACTERISTICS

Byron creek coal was obtained from Fernie, B.C. It is a medium volatile bituminous coal. Coal from the surface seams which had undergone partial oxidation was used in this work.

The coal had a heating value of 26.98 MJ/kg and a low sulphur content (0.6%). The as received moisture content ranged from 3 to 4%. Before firing the coal was air dried. The as-received size range of the coal was 50 mm x 0 and it was fired without crushing or screening. The results of the proximate, ultimate and ash analysis are given in Table 1.

THE PILOT SCALE AFBC

The apparatus is shown schematically in Fig. 1 and has been described in detail in a separate report (1). It consists of a fuel hopper capable of holding approximately 300 kg of coal, the combustor and freeboard and a multicyclone.

The combustor stands about 4.8 m high and has external dimensions of 0.94 by 0.97 m. The internal dimensions are 380 by 406 mm giving a bed area of 0.155 m^2. The bed, which is lined with firebricks and insulating refractory bricks, is instrumented with thermocouples and pressure probes. In addition there are two inserts on two opposite faces of the bed to allow water cooled tubes to pass through the bed. Although there is facility for up to 48 in-bed cooling tubes, in practice no more than 20 tubes were used at any given time. In-bed feeding was used throughout this work with the fuel being screw fed into the bed via a 67 mm diameter water cooled screw 114 mm above the distributor plate.

The air distributor consists of a 9.5 mm thick mild steel plate fitted with 100 bubble caps to allow even distribution of the fluidizing air. The 32 x 13 mm diameter stainless steel bubble caps are arranged in a 35 x 38 mm rectangular pitch. These bolts were drilled with a 6 mm hole through their central axis and four 3 mm holes just below the head of the bolt. This arrangement prevented "weeping" and caused the air to egress

horizontally. A 20 mm gap between the distributor plate and the bolt head allowed the plate to be covered with a dead layer of sand (Fig. 2).

The fuel feed system consisted of a coal hopper connected to a double screw feed system. Each screw is variable speed. The screw in the bottom of the hopper was connected via a flexible fiberglass hose to the second water-cooled conveying screw which delivered the coal directly into the bed. The hopper sat on an electronic weigh scale which permitted feed rates to be calculated from the change of weight per unit time.

The multicyclone was connected in series to the freeboard in a "flexible" stainless steel duct. The cyclone products could be either collected in a drum for non recycle tests or pneumatically reinjected back into the bed during tests with fly ash recycle.

The instrumentation was standard and consisted of NDIR recorders to continuously measure CO, CO_2 and SO_2 concentrations, a paramagnetic oxygen analyser and a chemiluminescent NO_x analyser. The temperatures in the bed, freeboard and cooling circuits were measured by "K type" thermocouples and the pressure drop across the bed by means of a manometer. With the exception of pressures all data was logged every 5 minues using an electronic data logger.

THE TEST PROGRAM

It was expected that the bed temperature would be the most important parameter affecting the combustion efficiency. Therefore three bed temperatures, 800°, 900° and 1000°C were chosen. Experience had also shown that with relatively unreactive fuels the second most important parameter is fluidizing velocities. The excess oxygen level is not particularly important (2,3). Three fluidizing velocities were chosen: 1.8 m/s (6 ft/s), 2.4 m/s (8 ft/s) and 3 m/s (10 ft/s) and one excess oxygen level of 4%.

Because the fuel is oxidized and relatively unreactive the other important parameter likely to affect combustion efficiency is recycle. For each test without recycle, a test was carried out under as nearly identical test conditions as possible with recycle. As it was difficult to control the pneumatic recycle precisely, recycle rate was not made part of the test matrix. Readings were taken after bed temperatures and emissions had been stabilized implying that a "steady state" had been achieved.

The recycle rate was measured by temporarily connecting the cyclone to a bin for a period of a few minutes and collecting the discharged material.

The recycle rate was then determined by weighing the discharged material and dividing the weight by the period of time during which it had been collected.

The determination of elutriated carbon required measurement of the fly ash weight and per cent combustibles trapped by the cyclone for the runs without recycle and only that passing the cyclone for recycle runs. The determination of the amount of carbon trapped by the cyclone was straightforward. The cyclone hopper was drained at the start and end of the "steady state" period of the test and the material collected was weighed and analysed for carbon.

The weight of fly ash passing the cyclone was determined by "batch-type" dust loading measurements using a filter system to provide a sample for carbon content measurement. Two or three dust loadings, each requiring about 15 minutes to obtain, were taken during each run.

The bed material was brown sand, which had a particle density of 2580 kg/m^3 and a bulk density of 1570 kg/m^3. A fresh charge was used for every 4 or 5 runs. This was considered satisfactory for the following reasons:

a) Sulphur capture was not a feature of these tests.
b) The ash from the coal was substantially elutriated.
c) Measurements indicated that the carbon retention in the bed was negligible.

All of the above indicate that the bed behaves essentially as an inert matrix.

In total 20 tests were carried out. Throughout this work in-bed feed was employed as it provides the best combustion efficiencies with relatively unreactive fuels (3). In-bed feeding also helps to reduce freeboard combustion of coal fines.

TEST RESULTS

The mean bed conditions and mean emissions are given in Tables 2 and 3 for the "steady state period". Bed temperatures were normally maintained within ± 5°C of mean values given in Table 2. CO emissions occasionally showed fluctuations to 1000 to 2000 ppm, due presumably to the sudden release of fines into the free board. All gas concentrations were fairly steady. The duration of the steady state periods was typically between 1 to 3 hours depending upon the time required to achieve "steady state".

FLUE GAS EMISSIONS

The concentrations of CO were found to decrease as the bed temperatures rose and tests with recycle appeared to have lower CO concentrations than tests without recycle (Fig. 3). As the data showed considerable scatter further analysis was not attempted.

The NO_x concentrations varied from 20 to 340 ppm. Recycle tests showed a linear increase in NO_x with bed temperature but no such correlation was evident for tests without recycle (Fig. 4).

The SO_2 concentrations varied between 200 and 350 ppm which represents a release of between 36 and 72% of the total sulphur contained in the fuel. Despite a relatively high natural $\lceil Ca/S \rceil$ ratio and a high $\lceil (Ca + K + Na/S) \rceil$ ratio of 1 and 1.3 respectively for the coal, there was no evidence that the fly ash was acting as a sorbent. With some fuels researchers have noticed that percentage captive of sulphur by alkali components in the ash is a function of bed temperature (4,5).

The mean oxygen concentrations varied between 3.7 and 4.7%, the desired value being 4%. The mean CO_2 concentrations in the flue gas varied between 13.6 and 15.3%. Calculations based on the ultimate analysis of the coal, coal feed rates and airflow rates together with the combustion efficiency indicated that the air flow meters must have been reading between 5 and 10% too low.

COMBUSTION EFFICIENCIES

Combustion efficiencies and carbon carryovers are given in Table 4 along with the appropriate bed parameters. In all, 9 tests were carried out without recycle and 10 tests with recycle.

When carbon carryover fcc was plotted against bed temperature, expressed as a reciprocal of the absolute temperature ($10^4/T$) for each of the 3 fluidizing velocities, it became clear that for tests without recycle the combustion efficiency is strongly affected by bed temperature and fluidizing velocity (Fig. 5). For the recycle test no such clear picture emerged, although carbon carryover does decrease as the bed temperature increases. Attempts to include the effects of recycle rate, expressed either directly or as the ratio of the recycle rate to the feed rate did not demonstrate any clear correlation.

When the carbon carryover, fcc, is correlated against bed temperature and fluidizing velocity expressed as,

$$fcc = a_o p^{a_1} \exp \frac{a_2}{T}$$

where, a_o, a_1 and a_2 are constants to be determined by the regression

$$p = \frac{gL}{U} 2$$

g = acceleration due to gravity

L = length of the bed side (0.406 m)

U = fluidizing velocity

T = absolute bed temperature

the results is the following equation

$$fcc = 0.139\ p^{-0.348} \exp\left(\frac{5740}{T}\right)$$

Durbin-Watson Statistic = 2.207

This correlation provides a good fit, the greatest difference between ($f_{observed}$-$f_{predicted}$) being 16%, see (Table 5). No such correlation, however, was found for the tests with recycle.

One interesting observation is that despite the presence of 2 to 20 tubes in the bed for the 9 runs without recycle the correlation is unaffected. On a priori grounds one might have expected some effect on the combustion efficiency due to the change in the hydrdodynamic environment produced in the bed.

The correlation obtained above is very similar to others obtained with unreactive fuels from a smaller bed, (241 mm in diameter). This unit was used at the combustion and carbonization laboratory before the construction of the present rig (2,3,5).

These results indicate that carbon carryover varies from 12 to 35% and combustion efficiencies from 69 to 90% without recycle. For tests with recycle the carbon carryover varies from 2 to 8% and the combustion efficiencies from 93 to 98%.

FREE BOARD TEMPERATURES

Figures 6, 7 and 8 show the freeboard temperatures as a function of height above the distributor. The degree of freeboard burning with both recycle and non-recycle increases with increasing fluidizing velocity. An increase in bed temperature however reduces the degree of combustion in the freeboard. The temperature profiles were obtained with "shielded" thermocouples but no attempt was made to account for the effect of radiation from the bed surface.

HEAT TRANSFER

During these studies bed temperatures were controlled by means of water cooled stainless steel tubes (nominal O.D. 21.3 mm, I.D. 15.8 mm). Tube numbers in the bed varied between 2 and 20. The cooling water inlet and outlet temperatures varied from 9 to 13°C and 30° to 90°C respectively and the water flow rate ranged from 150 to 500 kg/h.

The number of circuits, tubes and the heat transfer coefficients for water side H_i, bed side H_w and the overall H_o are given in Table 6. These were calculated using Grewal's program suitably modified for this study (6,7).

The overall heat transfer coefficients, H_o varied between 260 to 390 W/m^2K and the bed side heat transfer coefficients, H_w, varied between 300 to 500 W/m^2K. The majority of the bed side heat transfer coefficients lie between 300 - 400 W/m^2K, which is well within the normal range quoted in the literature for bubbling AFBC using coarse bed material (mean particle size dp~1mm) (8,9).

Attempts to plot H_w as a function of various bed parameters such as tube height and fluidizing velocity were unsuccessful. The most satisfactory correlation between the heat transfer coefficients and a bed parameter is that of bed temperature (Fig. 9), which shows that the heat transfer coefficient increases linearly with increasing bed temperature.

CONCLUSIONS

1. Byron Creek coal can be successfully burnt in a conventional bubbling atmospheric fluidized bed combustor.
2. With recycle combustion efficiencies as high as 98% can be achieved.
3. High temperatures (>900°C) and low fluidizing velocities (<2m/s) favour high combustion efficiencies.
4. The concentration of pollutents namely CO, SO_2 and NO_x were within acceptable limits. The CO varied from 100 to 1500 ppm, SO_2 from 200-370 ppm and NO_x from 20 to 350 ppm. The higher values for CO reflect the presence of occasional transient levels of CO of 1000 to 2000 ppm.
5. Heat transfer coefficients were measured. The majority of the bedside values ranged from 300-400 W/m^2K.

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Table 1 - Analytical data for Byron Creek coal

Proximate Analysis	Wt (%) (dry basis)
Ash	17.03
Volatile Matter	26.96
Fixed Carbon	56.01
Ultimate Analysis	
Carbon	70.96
Hydrogen	4.11
Sulphur	0.56
Nitrogen	1.09
Ash	17.03
Oxygen (by difference)	6.25
Gross Calorific Value	
MJ/kg (dry basis)	26.98
BTU/lb (dry basis)	11,597
Equilibrium Moisture	
Air dried	1.5
Ash Analysis	
SiO_2	47.27
Al_2O_3	29.35
Fe_2O_3	4.80
TiO_2	1.49
P_2O_5	0.45
CaO	5.82
MgO	1.36
SO_3	5.96
Na_2O	0.61
K_2O	0.55

Table 2 - Mean bed conditions

Test No.	Duration of steady state conditions h	Dry coal feed rate kg/h	Air flow fluidizing air m^3/h	Recycle air m^3/h	Total air m^3/h	Fluidizing velocity m/s	Bed temperature °C
1	1.5	37.7	285.6	0	285.6	2.1	921
2	1.75	47.7	383.2	0	383.2	3.0	989
3	1.0	46.1	320.9	0	320.9	2.2	816
5	2.0	53.9	399.5	0	399.5	2.9	895
6	1.5	32.8	231.5	12.9	244.4	1.8	897
7	1.75	30.2	217.5	0	217.5	1.7	1010
8	1.75	27.2	200.9	21.2	222.1	1.8	1015
9	1.0	41.1	291.2	0	291.2	2.3	1002
10	1.5	34.9	274.1	17.6	291.7	2.3	1009
11	2.5	35.6	243.4	0	243.4	1.7	894
12	1.0	34.2	225.5	18.2	243.7	1.8	904
13	2.0	34.7	293.9	24.5	318.4	2.3	911
14	1.75	43.1	365.9	24.5	390.4	3.0	987
15	2.0	37.9	256.5	0	256.5	1.7	811
16	1.75	35.2	242.4	24.5	266.9	1.8	802
17	2.5	46.3	330.4	0	330.4	2.2	791
18	2.5	44.2	375.7	24.5	400.2	2.9	897
19	1.5	59.5	430.2	0	430.2	2.9	824
20	2.0	49.8	398.9	39.0	438.5	2.9	797

Table 3 - Mean flue gas concentrations

Test No.	Recycle test	Paired test No.	Number of cooling tubes	O_2	CO_2	SO_2	NO_x	CO
				Gas concentrations				
				%	%	ppm	ppm	ppm
1	No	13	8	4.7	13.9	250	270	430
2	No	14	8	3.9	14.0	200	170	500
3	No	17	16	4.8	13.6	220	20	1180
5	No	18	16	3.7	14.4	300	260	900
6	Yes	11,12	16	3.8	14.9	250	200	1020
7	No	8	8	4.1	14.6	240	340	790
8	Yes	7	2	3.7	15.2	240	280	1460
9	No	10	2	4.0	15.0	300	300	690
10	Yes	9	4	3.8	15.2	370	270	310
11	No	6,12	4	3.5	15.0	270	-	700
12	Yes	6,11	8	3.6	15.3	280	-	310
13	Yes	1	8	4.2	14.6	290	220	700
14	Yes	2	8	3.8	15.3	250	270	120
15	No	16	6	4.2	14.5	290	250	680
16	Yes	15	11	3.8	15.4	240	130	970
17	Yes	3	15	3.8	14.9	350	160	340
18	Yes	5	11	4.0	14.9	320	230	240
19	No	20	20	4.5	14.1	350	260	1080
20	Yes	19	16	3.9	15.0	340	160	170

Table 4 - Combustion efficiencies and carbon carryover

Test No.	Recycle rate kg/h	Combustion efficiency %	Carbon carryover %	Paired test
1	0	83.2	19.4	13
2	0	86.7	15.4	14
3	0	75.2	28.7	17
4	-	-	-	-
5	0	77.2	26.4	18
6	7.0	95.2	5.6	11,12
7	0	89.8	11.8	8
8	6.1	98.3	2.0	7
9	0	87.7	14.3	10
10	9.6	95.6	5.1	9
11	0	84.3	18.2	6,12
12	7.0	95.0	5.8	6,11
13	24.0	95.6	5.1	1
14	17.4	95.4	5.3	2
15	0	78.5	24.9	16
16	12.8	95.8	4.9	15
17	8.4	92.7	8.4	3
18	18.8	94.0	7.0	5
19	0	69.4	35.4	20
20	22.5	92.8	8.3	19

Table 5 - Table of residual for non linear regression

Test No.	Observed Y	Predicted Y	Residual	Standardized residual
1	19.4	18.2	1.2	0.9
2	15.4	17.9	-2.5	-1.8
3	28.7	29.5	-0.8	-0.5
5	26.4	25.2	1.2	0.9
7	11.8	11.3	0.5	0.3
9	14.3	14.0	0.3	0.2
11	18.2	17.6	0.6	0.4
15	24.9	25.7	-0.8	-0.6
19	35.4	34.9	+0.5	0.4

Table 6 - Heat transfer coefficients

Run No.	No. of tubes	Height (m)	T bed (°C)	Fluidizing velocity (m/s)	Hi(W/m^2K)	Ho(W/m^2K)	Hw(W/m^2K)
1.1	4	0.4171	921	2.13	5791	301	350
1.2	4	0.3764	921	2.13	6123	326	382
2.1	4	0.4171	989	3.01	5977	312	364
2.2	4	0.3764	989	3.01	6148	331	388
3.1	4	0.4171	816	2.18	5806	268	306
3.2	4	0.3764	816	2.18	5795	283	327
3.3	4	0.2951	816	2.18	5733	284	327
3.4	4	0.2545	816	2.18	5895	301	350
5.1	4	0.4171	895	2.91	5309	293	341
5.2	4	0.3764	895	2.91	5196	302	355
5.3	4	0.2951	895	2.91	5074	302	355
5.4	4	0.2545	895	2.91	5084	314	371
6.1	4	0.4171	897	1.78	4361	311	373
6.3	4	0.3764	897	1.78	5450	306	358
7.1	2	0.4171	1010	1.74	5524	356	429
8.1	2	0.4171	1015	1.78	6435	352	416
10.1	2	0.4171	1009	2.33	6107	329	386
10.2	2	0.3764	1009	2.33	6213	366	438
11.1	2	0.4171	894	1.73	3034	324	414
11.2	2	0.3764	894	1.73	3035	325	415
11.3	2	0.4171	894	1.73	2943	309	391
11.5	2	0.3764	894	1.73	3196	347	446
12.1	2	0.4171	904	1.79	3275	318	399
12.2	2	0.3764	904	1.79	3199	325	411
12.3	2	0.4171	904	1.79	3468	323	404
12.5	2	0.3764	904	1.79	3516	313	387
13.1	2	0.4171	911	2.25	6008	314	366
13.2	2	0.3764	911	2.25	2636	273	341
13.3	2	0.4171	911	2.25	5838	308	359
13.4	2	0.3764	911	2.25	6000	312	364
14.2	2	0.3764	987	3.01	3469	360	457

Table 6 - Heat transfer coefficients (Cont'd)

Run No.	No. of tubes	Height (m)	T bed (°C)	Fluidizing velocity (m/s)	Hi(W/m^2K)	Ho(W/m^2K)	Hw(W/m^2K)
14.3	2	0.4171	987	3.01	3881	347	434
14.5	2	0.3764	987	3.01	3514	393	516
15.1	2	0.4171	811	1.73	5589	292	340
15.2	2	0.3764	811	1.73	5567	297	346
15.3	3	0.4171	811	1.73	5379	310	365
15.4	2	0.2951	811	1.73	5378	303	355
15.5	2	0.3764	811	1.73	5567	307	359
16.1	2	0.4171	802	1.78	4788	291	343
16.2	2	0.3764	802	1.78	5601	297	346
16.3	3	0.4171	802	1.78	4836	298	351
16.4	2	0.2951	802	1.78	5642	318	375
16.5	2	0.3764	802	1.78	5321	308	362
17.1	3	0.4171	791	2.18	3620	272	326
17.2	3	0.3764	791	2.18	3328	297	366
17.3	3	0.2951	791	2.18	3023	262	319
17.4	3	0.2545	791	2.18	3371	265	319
17.5	3	0.3764	791	2.18	3708	262	310
18.1	1	0.4171	897	2.92	2344	315	420
18.2	3	0.3764	897	2.92	4089	314	381
18.3	3	0.2951	897	2.92	3689	295	358
18.4	3	0.2545	897	2.92	4291	296	353
18.5	1	0.3764	897	2.92	2935	310	394
19.1	4	0.4171	824	2.94	5846	288	333
19.2	4	0.3764	824	2.94	5768	269	308
19.3	4	0.2951	824	2.94	5826	279	321
19.4	4	0.2545	824	2.94	5765	274	315
19.5	4	0.1732	824	2.94	5554	261	299
20.2	4	0.3764	797	2.92	3728	280	336
20.3	4	0.2951	797	2.92	3629	265	316
20.4	4	0.2545	797	2.92	3349	268	322
20.5	4	0.1732	797	2.92	3007	253	305

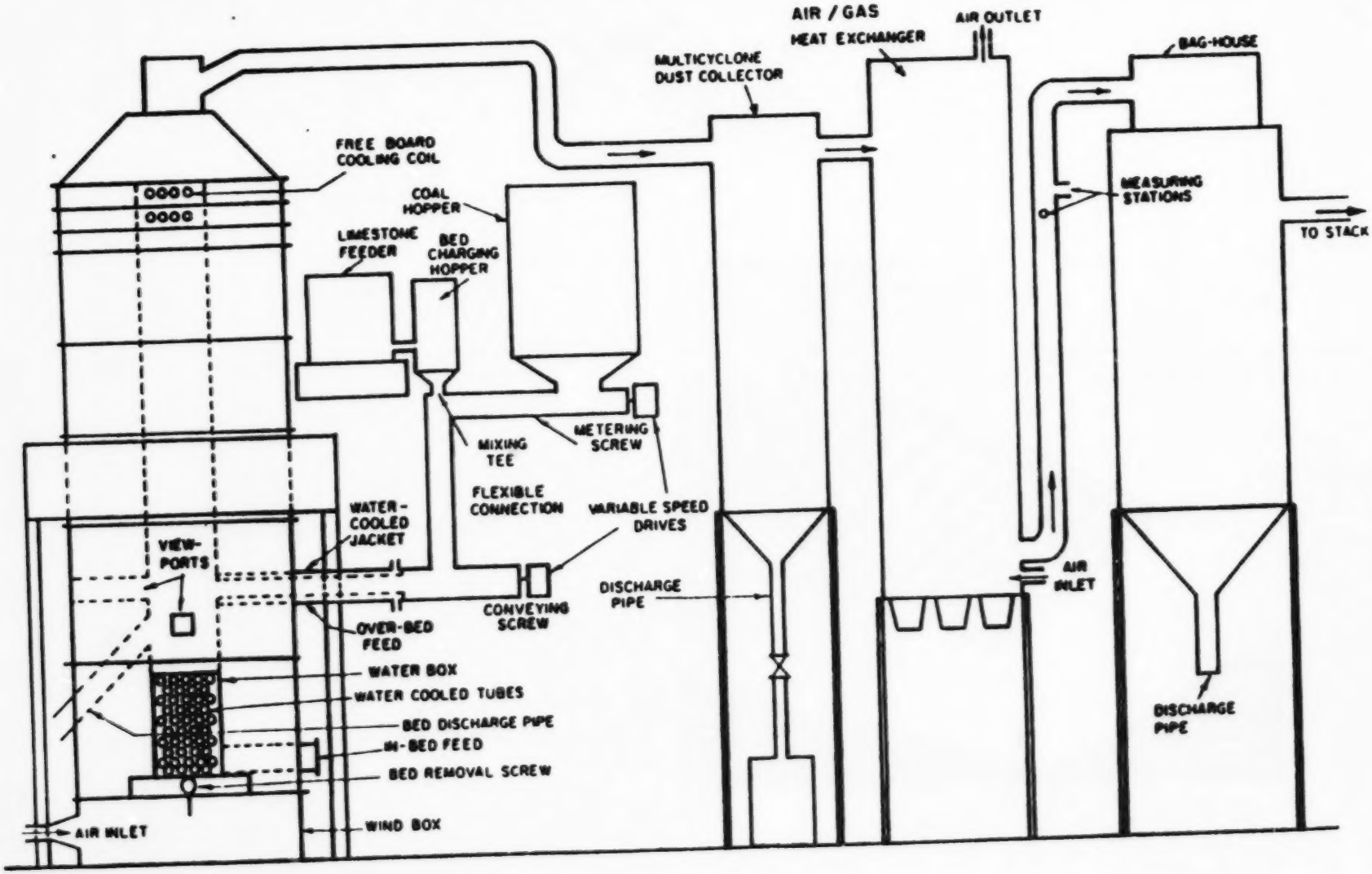
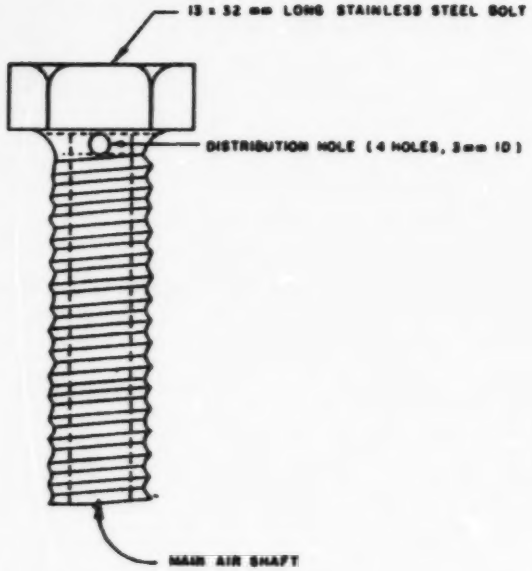


Figure 1 - Schematic of the Mark II fluidized bed combustor.



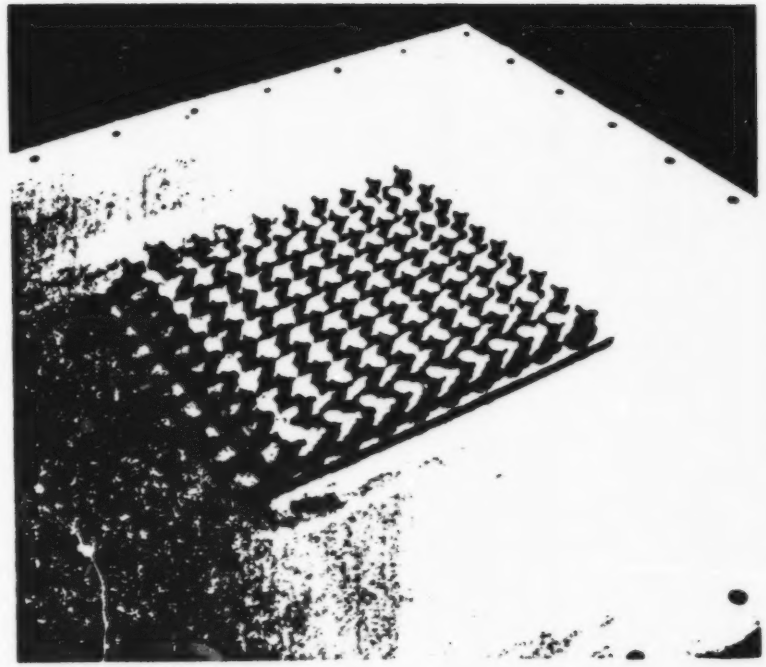


Figure 2- Details of the distributor design.

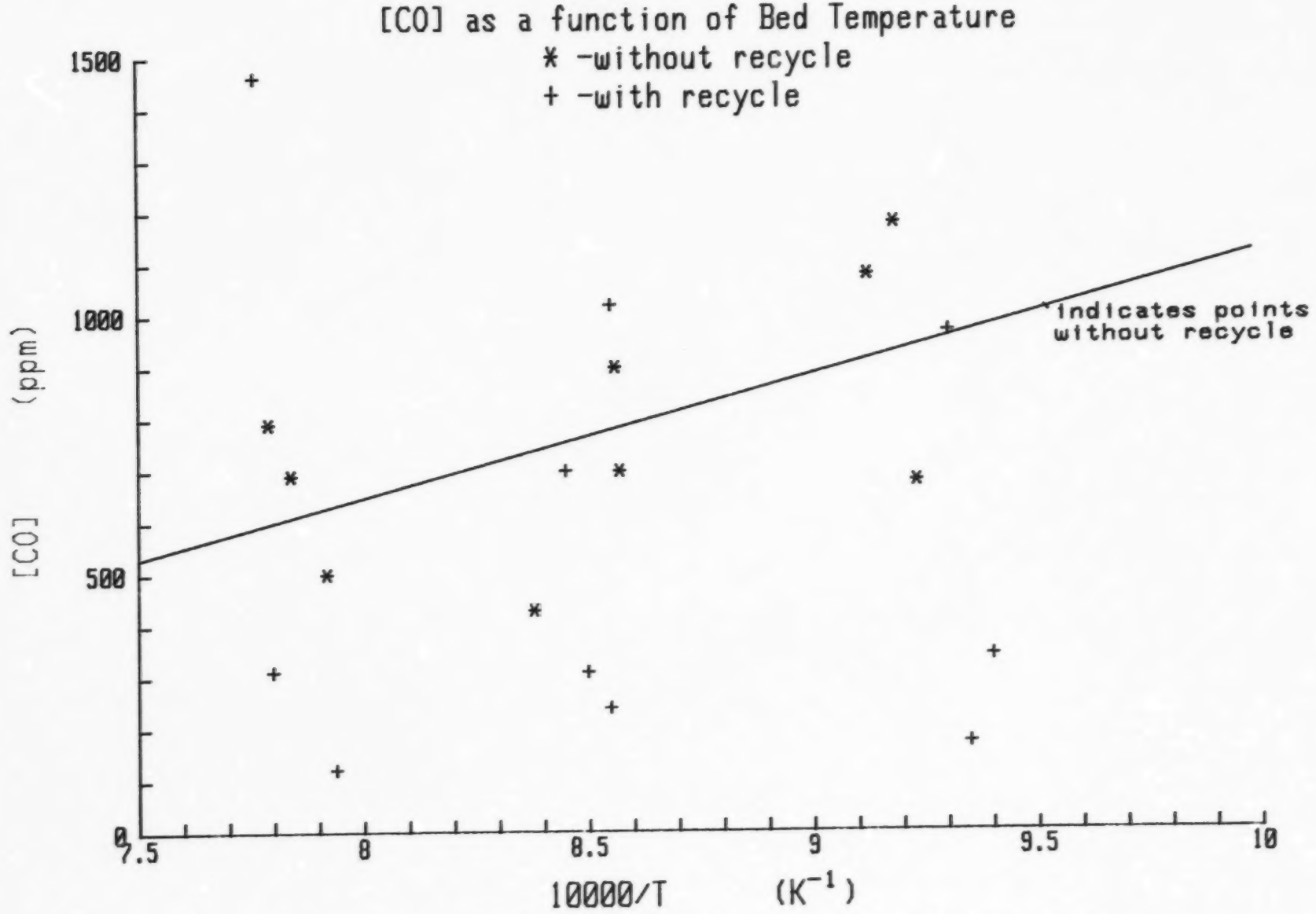


Figure 3: [CO] as a function of Bed Temperature

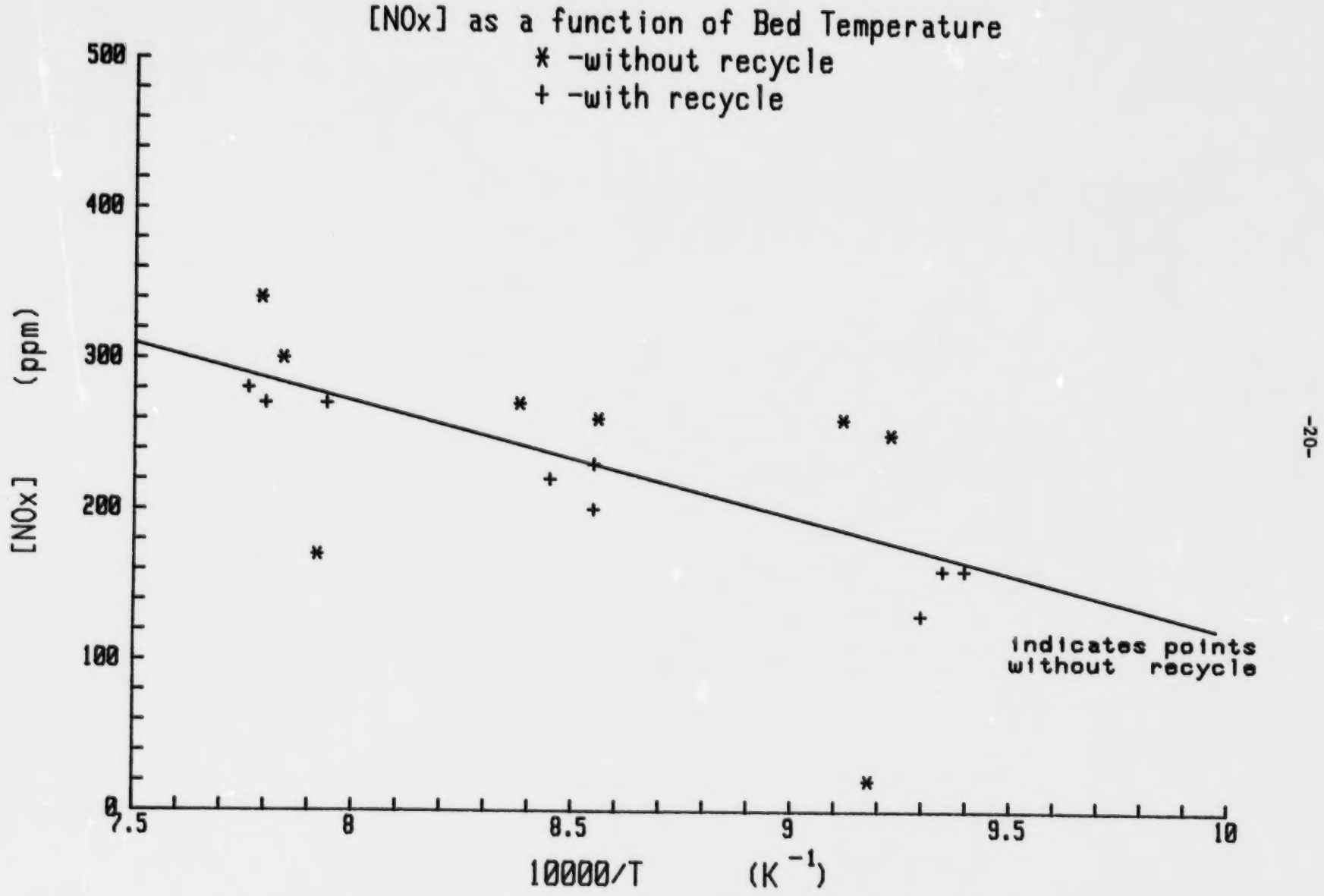


Figure 4: [NOx] as a function of Bed Temperature

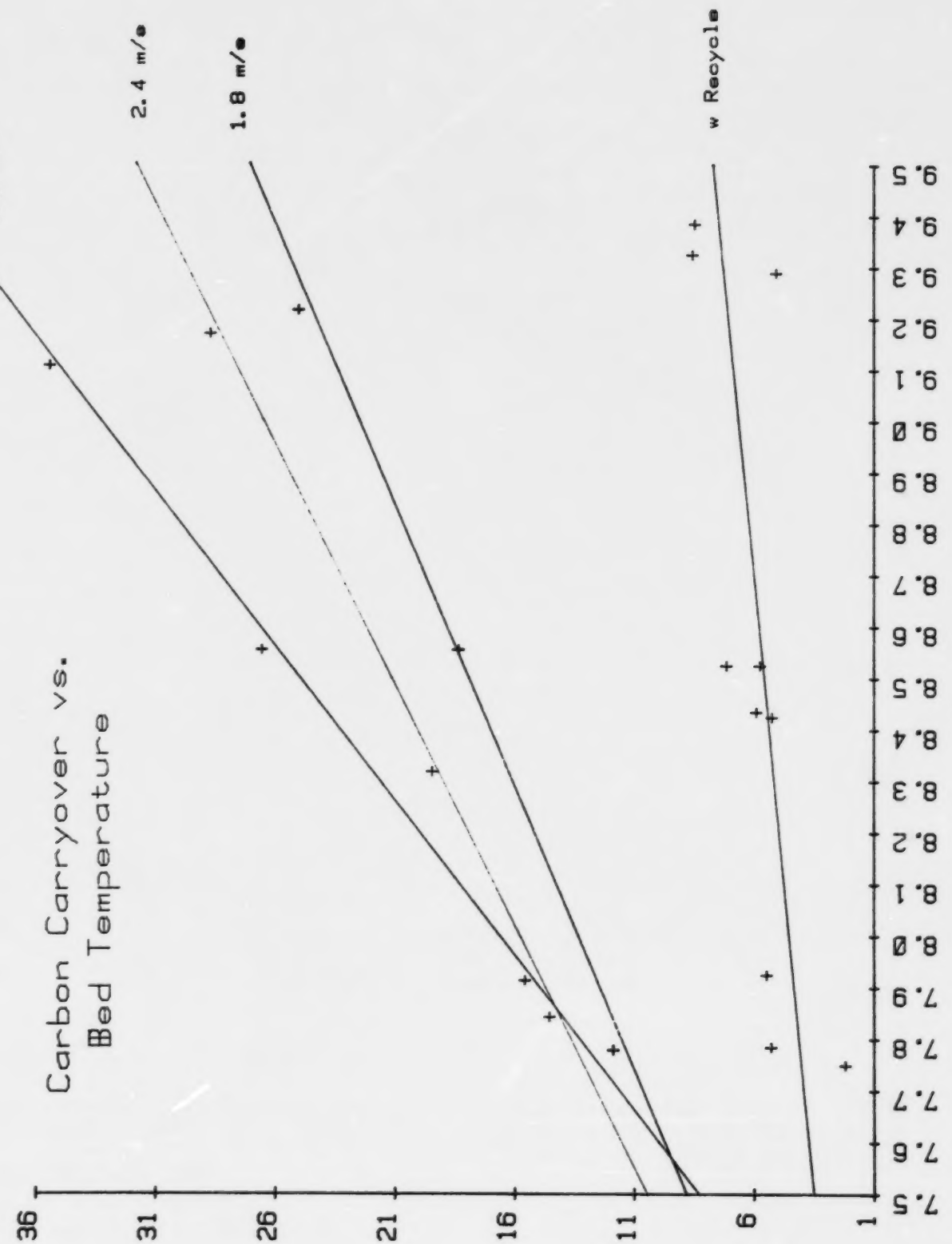

Carbon Carryover vs.
Bed Temperature
3.0 m/s
2.4 m/s
1.8 m/s
w Recycle
Carbon Carryover (%)
Bed Temperature (10000/T)
36
31
26
21
16
11
6
1
7.5
7.6
7.7
7.8
7.9
8.0
8.1
8.2
8.3
8.4
8.5
8.6
8.7
8.8
8.9
9.0
9.1
9.2
9.3
9.4
9.5

Figure 5

BED AND FREEBOARD TEMPERATURE PROFILE - BYRON CREEK COAL

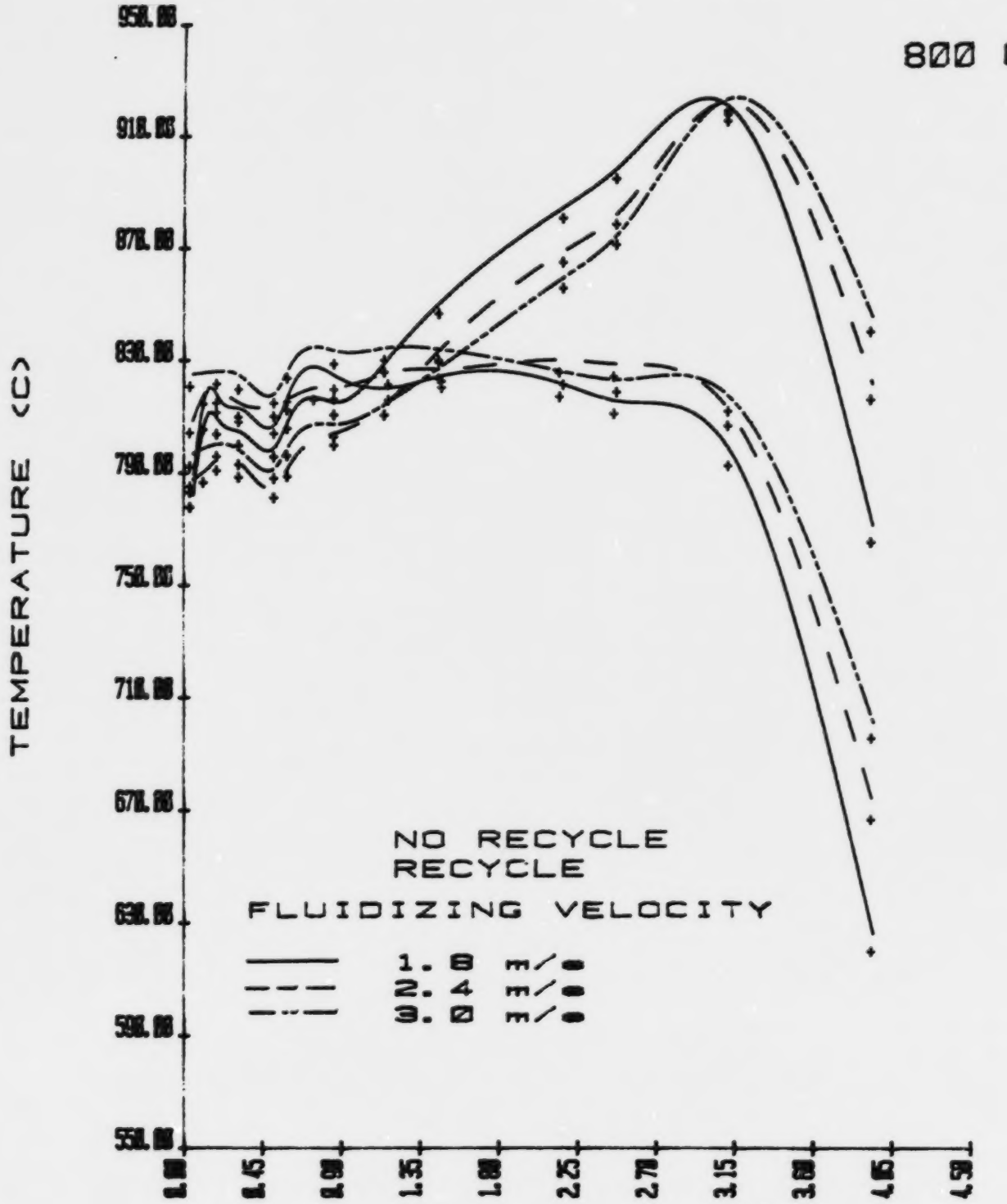


Figure 6

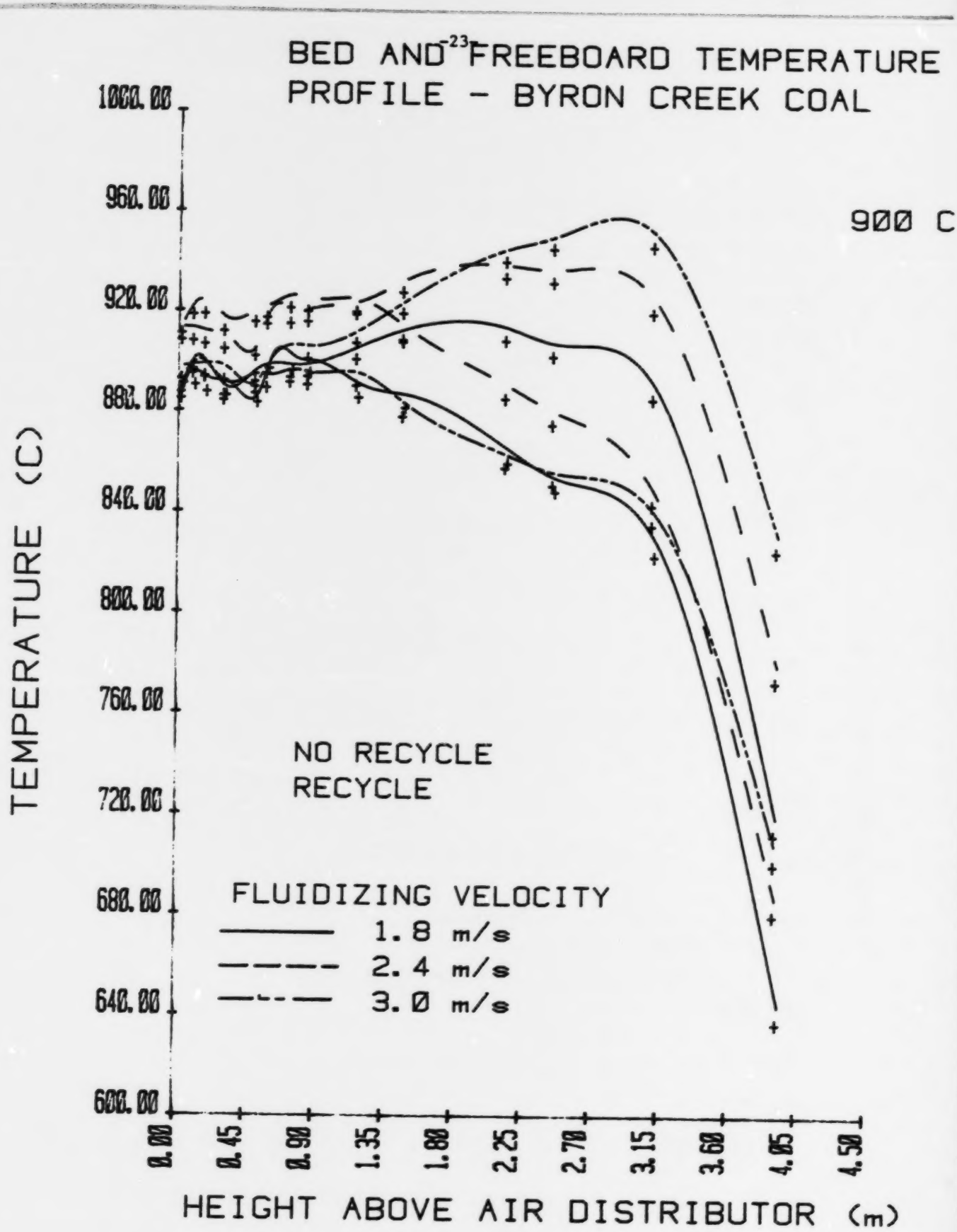

BED AND FREEBOARD TEMPERATURE PROFILE - BYRON CREEK COAL
900 C
TEMPERATURE (C)
1000.00
960.00
920.00
880.00
840.00
800.00
760.00
720.00
680.00
640.00
600.00
NO RECYCLE
RECYCLE
FLUIDIZING VELOCITY
1.8 m/s
2.4 m/s
3.0 m/s
0.00
0.45
0.90
1.35
1.80
2.25
2.70
3.15
3.60
4.05
4.50
HEIGHT ABOVE AIR DISTRIBUTOR (m)

Figure 7

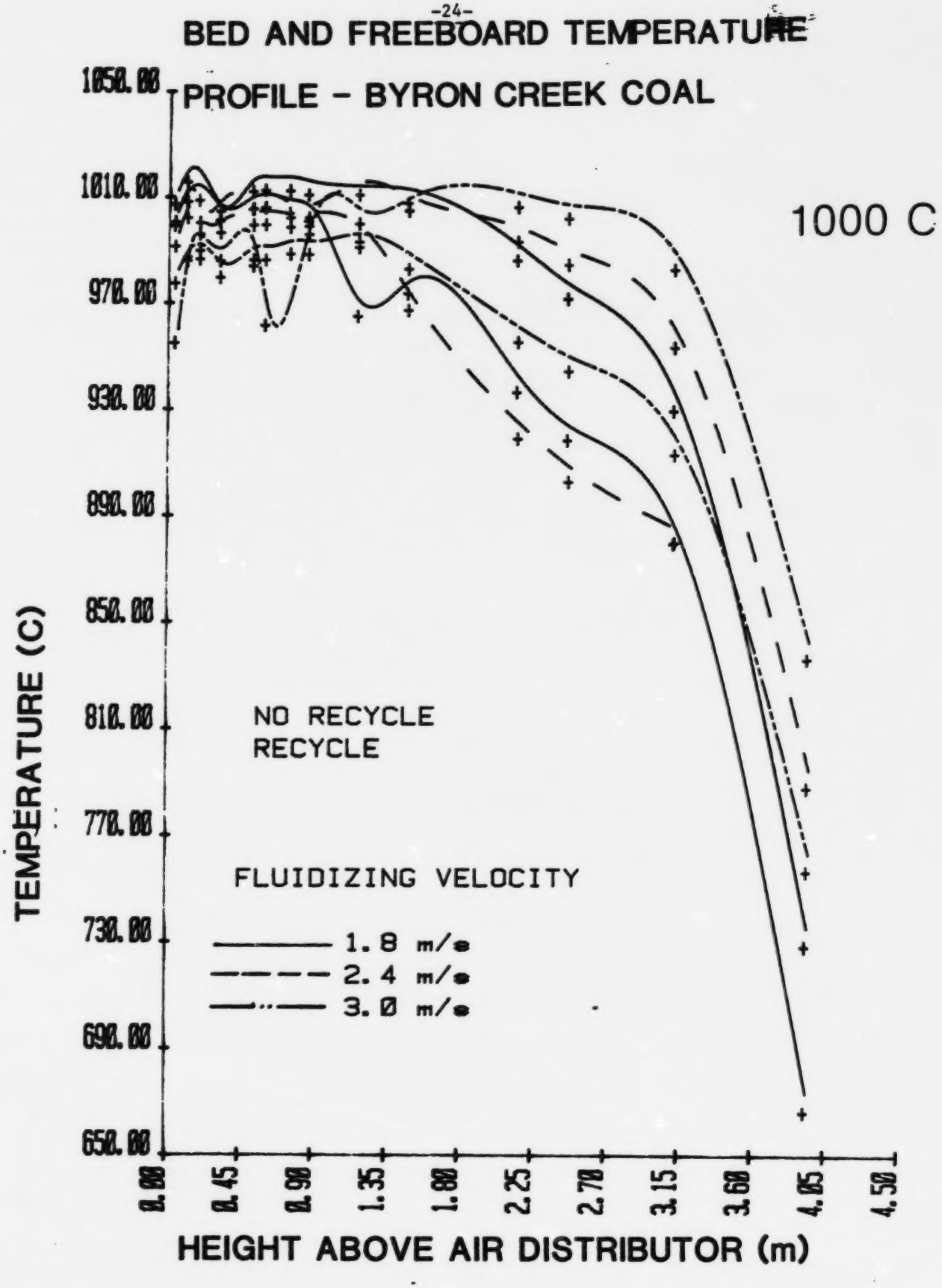

BED AND FREEBOARD TEMPERATURE
PROFILE - BYRON CREEK COAL
1050.00
1010.00
970.00
930.00
890.00
850.00
810.00
770.00
730.00
690.00
650.00
TEMPERATURE (C)
1000 C
NO RECYCLE
RECYCLE
FLUIDIZING VELOCITY
1.8 m/s
2.4 m/s
3.0 m/s
0.00
0.45
0.90
1.35
1.80
2.25
2.70
3.15
3.60
4.05
4.50
HEIGHT ABOVE AIR DISTRIBUTOR (m)

Figure 8

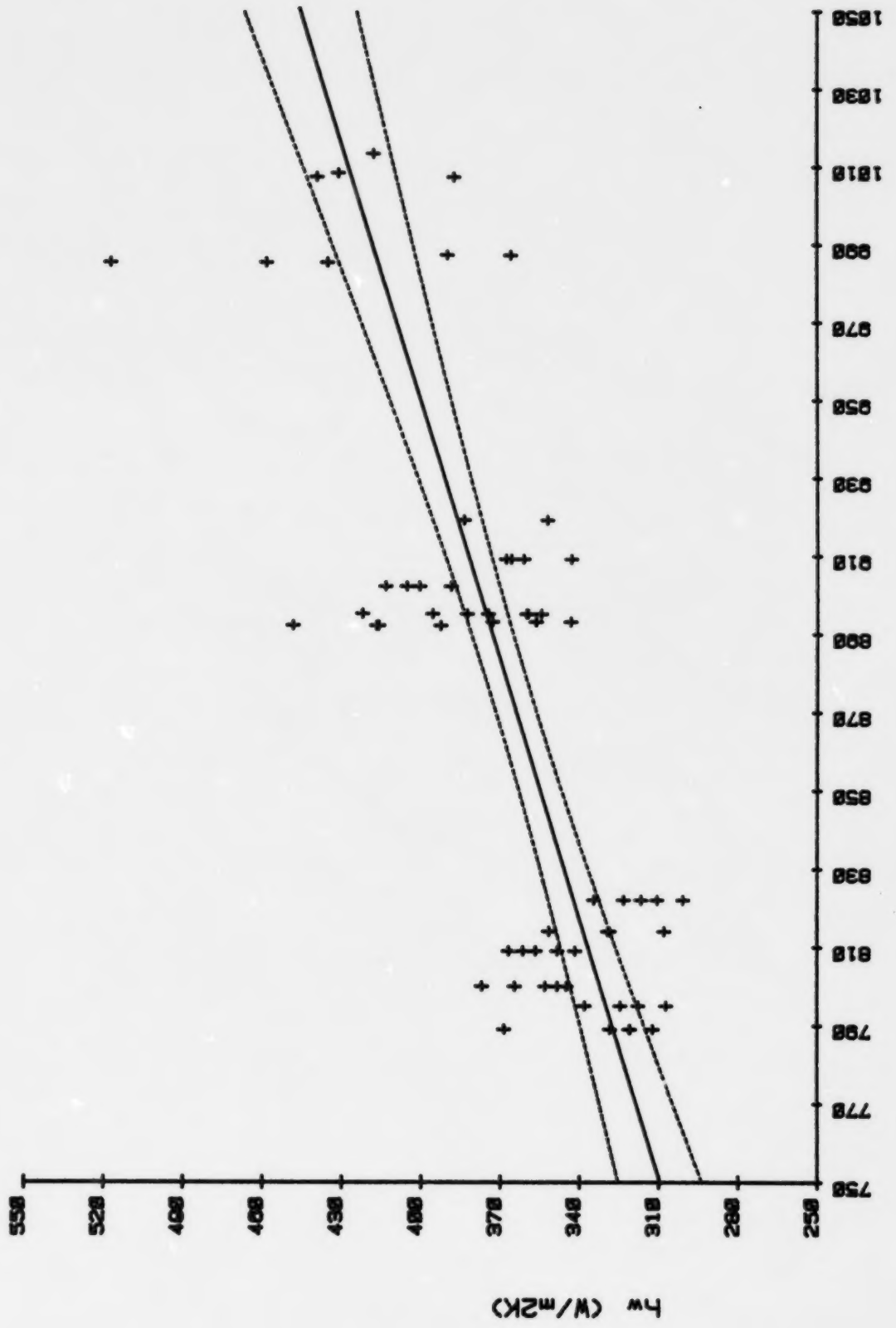

hw vs. Bed Temperature
hw (W/m2K)
Bed Temperature (C)
750
770
790
810
830
850
870
890
910
930
950
970
990
1010
1030
1050
250
290
330
370
410
450
490
530
570

Figure 9